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Distribution and potential of bioenergy resources from agricultural activities in Mexico

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ABSTRACT

Biomass is the most abundant and versatile form of renewable energy in the world. The bioenergy production from crop residues is compatible with both food and energy production. Currently, several technologies are available for transforming crop residues into utilizable energy such as direct combustion and fermentation. Mexico is the third largest country in LAC in terms of the cropland area and would become a central focus of attention for the production of biofuels. In this paper we examined the type, location and quantities of various crop residues in Mexico to evaluate their potential for conversion into bioenergy through combustion and fermentation. It was estimated that 75.73 million tons of dry matter was generated from 20 crops in Mexico. From this biomass, 60.13 million tons corresponds to primary crop residues mainly from corn straw, sorghum straw, tops/leaves of sugarcane and wheat straw. The generation of secondary crop residues accounted for 15.60 million tons to which sugarcane bagasse, corncobs, maguey bagasse and coffee pulp were the main contributors. The distribution of this biomass showed that several Mexican municipalities had very high by-product potentials where each municipality could have an installed capacity of 78 MW (via direct combustion) or 0.3 million m^3 of bioethanol per year (via anaerobic fermentation). The identification of these municipalities where the biomass potential is high is important since it constitutes the first step towards evaluating the current biomass availability and accurately estimating the bioenergy production capacity from crop residues.

Contents

1. Introduction

The world total primary energy consumption was 11,400 million tons oil equivalent in 2005. Fossil fuels were by far the dominant energy source with oil, coal and natural gas accounting for 80% of the total. The Asia-Pacific was the largest energy-consuming region with China, Japan, India and South Korea as the most important consumers (Fig. 1). Due to this level of use, the current world reserve/production ratio for oil is 41.6 years, while the ratios for gas natural and coal are 60.3 and 133 years, respectively (Fig. 2; [1]). Yet the growing environmental requirements are forcing a shift to new energy schemes in the near future, increasing the currently limited participation of renewable resources (13% of the total world consumption). Biomass is the most abundant and versatile form of renewable energy in the

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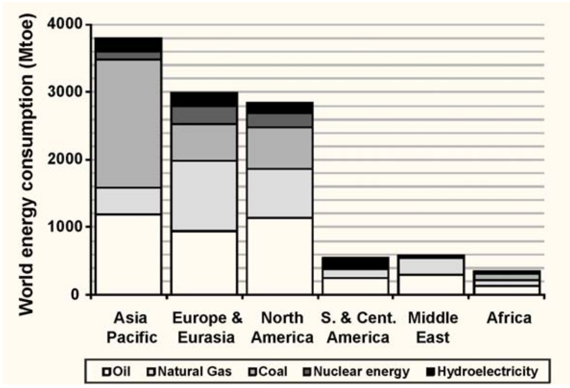

Fig. 1. The world primary energy consumption by region and fuel type, 2007 (11,099 million tons oil equivalent, Mtoe).

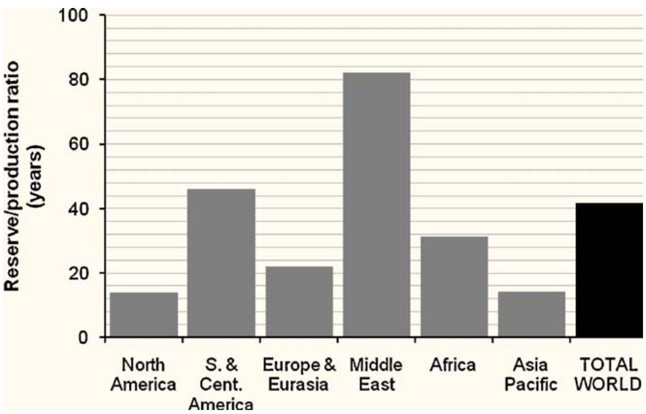

Fig. 2. The oil reserve/production ratio for proven resources worldwide.

world. Biomass includes any biological material derived from living, or recently living organisms, such as virgin wood, energy crops, agricultural residues, food waste, and industrial waste and co-products. The production of biomass energy from wood and/or energy crops is controversial since these compete against food crops for land and fresh water. Their cultivation could also contribute to pollution problems due to the fertilizers and pesticides used for the intensive farming of these crops [2]. An alternative approach is to use crop residues that are compatible with both food and energy production. Currently, several technologies are available for transforming crop residues into utilizable energy as liquid and gaseous biofuels or electricity. Thermo-chemical technologies such as direct combustion, pyrolysis and gasification supply heat, steam, power and biofuels. Biological technologies such as fermentation and anaerobic digestion supply alcohols, methane, hydrogen and inclusive biodiesel [3]. Some of these technologies are sufficiently advanced to be implemented immediately.

Latin America and the Caribbean (LAC) have been highlighted as a region with a significant advantage in the production of biofuels due to their natural biomass potential [4]. Currently, there are 1.6 billon ha of cropland in use worldwide and LAC is one of the majority regions with 13%. It has been estimated that the potential for cropland expansion could increase from 1.6 to 4.2 billon ha, after which LAC will represent one quarter of the total [5]. In this respect, Mexico is the third largest country in LAC in terms of the cropland area, following Brazil and Argentina [6]. In 2007, the cultivated area was 21.7 million ha with an agricultural production of 270 million tons. Traditional crops like maize occupied 40% of the total cultivated area whereas sorghum, beans, oats, sugarcane, wheat and barley occupied almost 30% [7]. Currently, the residual biomass generated from these activities could have diverse uses such as animal feed, mulch, burning and compost [8]. Nevertheless, the biomass utilization for obtaining energy is an attractive option for the rural sector due to multiple potential social benefits [9]. In this way, Mexico would become a central focus of attention for the production of biofuels, a field that is still in the early stages of exploration. Before promoting biofuel production, it is first necessary to evaluate the natural potential of biomass as a starting point for strategic planning, to secure a stable food supply and the appropriate environmental protection standards. In this paper we examined the type, location and quantities of various crop residues in Mexico to evaluate their potential for conversion into bioenergy through thermo-chemical and biological technologies.

2. Methodology

The crop residues were divided into two main categories: (a) primary crop residues (PCR), including residues remaining in the fields after harvest, and (b) secondary crop residues (SCR) that were generated by processing the harvested portions of the crop. For the estimation of the crop residues, the crop residue index (CRI) was used, which is defined as the ratio of the dry weight of the residue produced to the total crop produced [10]. The crops considered in this study, their annual production and their CRIs were enlisted in Tables 1 and 2.

The biomass potentials for the main crops (PCR plus SCR) and the total biomass potential (sum of all the crops analyzed) were represented in thematic maps at the municipal level using ArcGIS 9.3 [16]. According to the National Statistics, Geography and Informatics Institute (INEGI), Mexico includes a total of 2439 municipalities in 31 states. The state with the greatest of municipalities is Oaxaca with 570. In this regard, the municipalities of Oaxaca were grouped into their corresponding political districts (30 districts) for convenience in data manipulations. The biomass potentials in each thematic map were divided into six ranges according to Table 3. These ranges were useful for converting the biomass potentials into the predicted bioenergy output by direct combustion and fermentation calculations. The main parameters for the direct combustion calculations were an average calorific value of 15 MJ/kg of dry matter and a 15% of conversion efficiency [3]. For the biomass-to-ethanol conversions, an average factor of 240 L/ton of lignocellulosic biomass was used [17]. In both cases, 50% biomass availability was assumed.

3. Results and discussion

3.1. The estimation of primary and secondary crop residues

For 2006, it was estimated that Mexico had 75.73 million of tons of dry matter that potentially could be transformed into bioenergy. The PCR generation was approximately 60.13 million tons of dry matter, of which the main categories were corn stalks, sorghum stalks, tops and leaves from sugarcane and wheat straw, in descending order. Other important by-products were barley straw, common bean straw and cotton stalks (Table 1). A remarkable fact with respect to the PCR conversion into bioenergy is that their current availability is unknown because, in many districts, a fraction of these residues was recycled to the land for agronomic uses or, more commonly, used for animal feed. These PCR are very important for the animal production in developing countries. A previous study shows that the total feed energy suitable for ruminant livestock consists of 53.9% permanent pasture, 20.9% forage, 23.6% crop residues, 0.5% grain, 0.2% oilseeds and 1.0% agro-industrial by-products [18]. However, the crop residues alone cannot sustain the animal production because of their low

Table 1
Agricultural crops, annual production, crop residue index and estimation of primary crop residues (PCR).

Crop	PAR	Crop residue index[a]	Annual production, 2006[b]	PCR[c]	%
Barley	Straw/stalk	2.3	0.87	2.00	3.32
Common beans		1.3	1.35	1.75	2.91
Chickpea		1.3	0.16	0.21	0.35
Lentil		1.3	0.01	0.01	0.02
Fava bean		1.3	0.02	0.03	0.05
Rice		1.5	0.34	0.51	0.84
Wheat		1.5	3.38	5.07	8.43
Canola		1.8	0.01	0.01	0.02
Cotton		3.0	0.45	1.34	2.23
Corn		1.5	21.89	32.83	54.60
Safflower		1.5	0.07	0.11	0.18
Sesame		1.8	0.02	0.04	0.06
Sorghum		1.5	5.52	8.28	13.77
Soybean		1.5	0.08	0.12	0.20
Tobacco		5.0	0.02	0.10	0.16
Sugarcane	Tops/leaves	0.15	50.55	7.58	12.61
Groundnut	Haulms	2.0	0.07	0.14	0.23
Total			84.81	60.13	100.00

Notes: [a]expressed as kg dry matter/kg crop produced; the index could vary with the agricultural practice, from [11]; [b]expressed as million tons; [c]expressed as million tons of dry matter.

Table 2
Agricultural crops, annual production, crop residue index and estimation of secondary crop residues (SCR).

Crop	SAR	Crop residue index[a]	Annual production, 2006[b]	SCR[c]	%
Corn	Cobs	0.30	21.89	6.57	39.81
Rice	Husk	0.30	0.34	0.10	0.62
Groundnut	Shells	0.30	0.07	0.02	0.12
Cotton	Gin trash	0.10	0.45	0.04	0.27
Coffee cherry	Pulp	0.24	1.49	0.36	2.16
	Husk	0.10		0.15	0.90
Agave (mezcal)	Bagasse	0.12	1.22	0.15	0.89
Maguey (pulque) [d]		5.5[e]	0.28	1.53	9.26
Sugarcane		0.15	50.55	7.58	45.97
Total			76.28	16.50	100.0

Notes: [a]unless otherwise noted, the index was expressed as kg dry matter/kg crop produced and could vary with the agricultural practice, from [11–15]; [b]expressed as million tons; [c]expressed as million tons of dry matter; [d]expressed in thousands of liters; [e]expressed as kg dry matter per liter.

Table 3
Bioenergy potential divided into ranges.

Range	Biomass potential (ton DM[a]/year)	Bioenergy potential[b] (kW)	Ethanol potential[b] (m^3 EtOH/year)
A	280,320.1–2,181,021	10,000.1–77,805	33,638.1–261,723
B	140,160.1–280,320	5,000.1–10,000	16,819.1–33,638
C	28,000.1–140,160	999.1–5,000	3,360.1–16,819
D	5600.1–28,000	200.1–999	672.1–3,360
E	140.1–5,600	5.1–200	17.1–672
F	0-140	0–5	0–17

Notes: [a]dry matter; [b]it was assumed that only 50% of biomass can be considered available for conversion.

nutritional quality; they are deficient in protein, phosphorus and calcium. Their unbalanced nutritional quality causes a significant limitation to ruminant livestock productivity [19]. For that reason, animal feed should always be supplemented with forages, which account for over 80% of the metabolizable energy for grass-eaters [18]. Because of lack of information on the PCR availability in Mexico and considering that the main use is animal feed, a reasonable approximation of the PCR availability could be calculated based on livestock units (LU) and the amount of forage available in dry matter (DM/LU). For 2005, approximately 34.71 million LU were reported by the Secretary of Agriculture, Ranching, Rural Development, Fisheries, and Food Supply (SAGARPA). Taking into account only the forage crop production of 16.42 million tons from nine vegetable varieties (without counting crop residues), the amount of forage per LU was 0.47, thus showing a deficiency in the feed resources. But by including the corn residues only, that amount increased to 1.61, which falls into the category of high dry matter availability [20]. So it seems that in fact there are PCR remaining in the land and their to bioenergy does not endanger biomass resources for animal requirements. In fact, some studies have shown that in some Mexican municipalities, the burning of agricultural waste constitutes an important source of air pollutant emissions [21].

Regarding the SCR, it was estimated that 16.50 million tons of dry matter was generated in 2006. The main by-products were sugarcane bagasse, corncobs, maguey bagasse and pulp from coffee cherry (Table 2). The estimation of SCR could be much higher if the by-products are included from the processing of fruit for juice, concentrates and preserves. However, this evaluation is not feasible from the crop residue index and therefore it was not

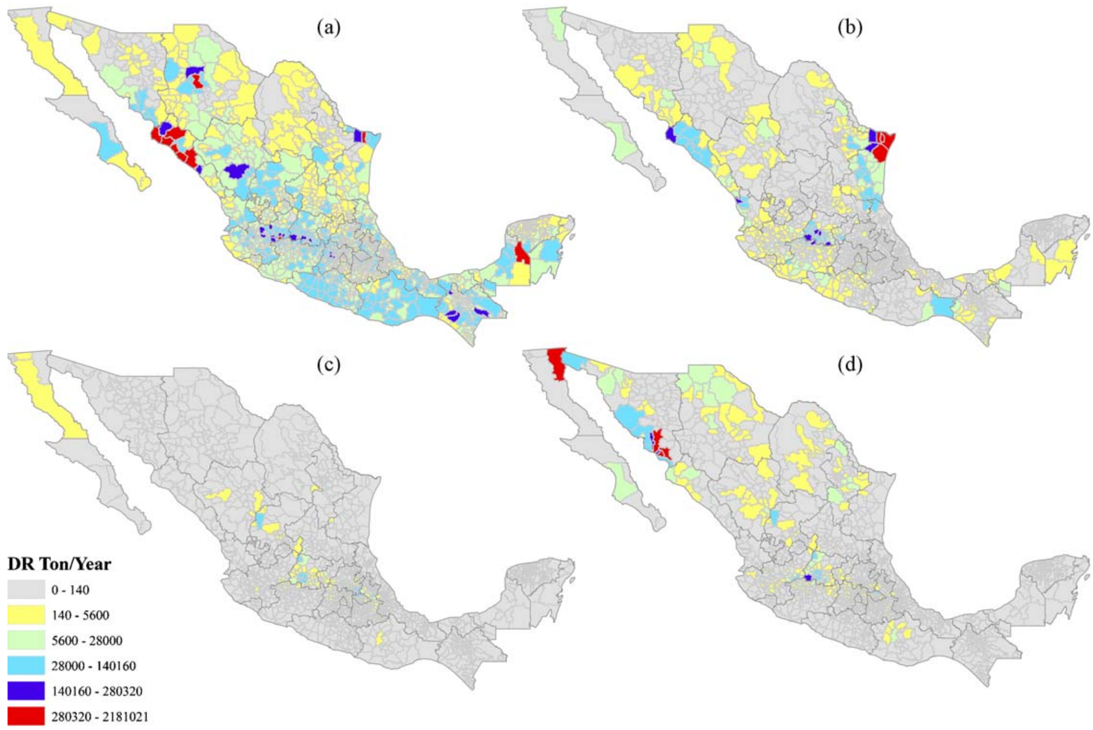

Fig. 3. The distributions of biomass from (a) corn stover and cobs, (b) sorghum straw, (c) barley straw and (d) wheat straw. Notes: the colors indicate the dry residues tons per year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

considered in this work. The main advantages of using SCR for energy production are that they tend to be concentrated in a relatively small geographic area (processing plants) and are not widely used for animal feed. Thus the SCR could be an important local supply of bioenergetic resources.

3.2. The spatial distribution of crop residues

The biomass potentials were represented in thematic maps at municipal level classified into six ranges where the highest potential correspond to range A and the lowest potential

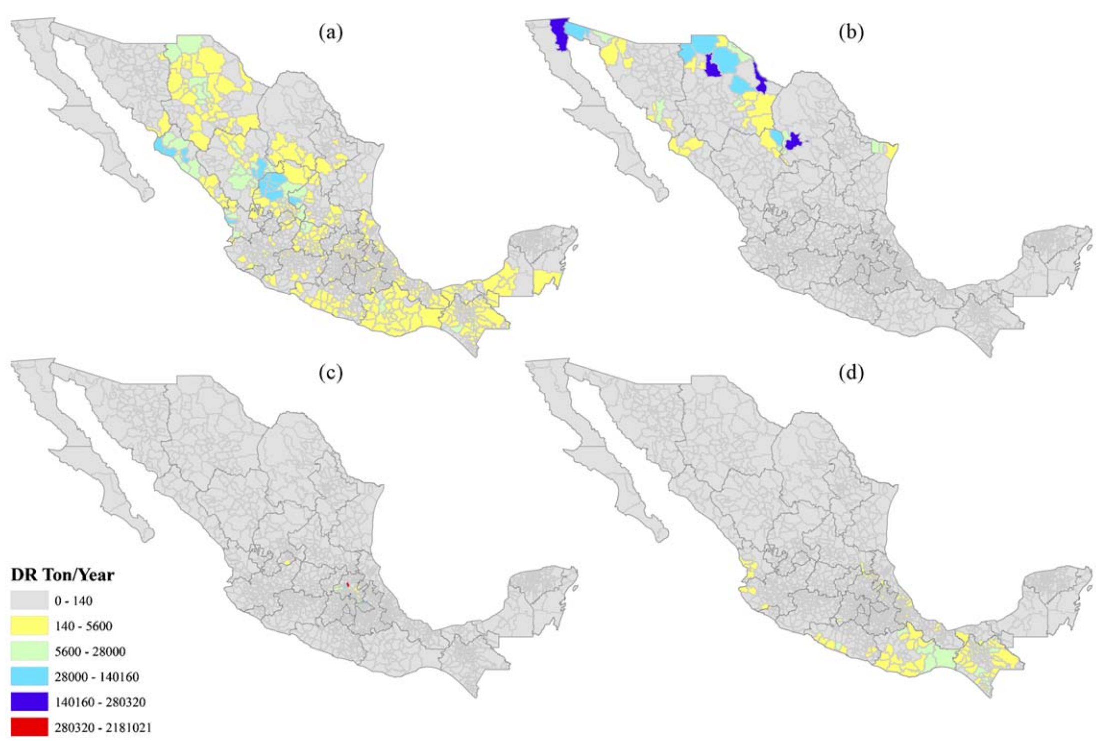

Fig. 4. The distributions of biomass from (a) bean straw, (b) cotton straw and gin trash, (c) pulque maguey bagasse and (d) coffee pulp and husk. Notes: the colors indicate the dry residues tons per year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

correspond to range F (see Table 3). In this way, Fig. 3 shows the spatial distribution of biomass resources from the main cereal crops in Mexico. The corn by-products (stalks/cobs) have the highest potential, accounting for a total of 39.4 million tons of dry matter distributed nationally (Fig. 3a). These findings are in accordance with previous studies reporting that 133.66 million tons of corn stover matter distributed nationally was available in North America, of which approximately one quarter was from Mexico and three quarters from the US [22,23]. In Mexico, the corn crop has a high social and economic value, indicated by the fact that 30% of the employed population in the primary sector is dedicated to the cultivation of this cereal. There are two production systems, subsistence and commercial farming. Subsistence farming accounts for 85% of the production in cases where the land distribution is less than or equal to 5 ha per family. A significant part of its production is destined for self-consumption, generating the main income for these families. In commercial farming, the main motive is to satisfy the agro-industry in which multiple corn products are processed, such as tortillas, flour, starch, cereals, animal food, and other products. In commercial production systems, 11% of land was distributed in 5–10 ha farms and 4% to farms larger than 10 ha [24]. In this way, despite corn being the main crop in Mexico, only a few municipalities located in the states of Sinaloa, Jalisco, Chihuahua, Tamaulipas and Campeche had the highest production potentials estimated between 280,320 and 2,181,021 tons of dry matter per year, range A (see Table 3 and Fig. 3a).

Fig. 3b–d shows the distributions of sorghum, barley and wheat biomass, respectively. The sorghum straw was the second highest potential biomass source in Mexico. It was distributed nationally but the only municipalities with a large accumulation of residues were in the state of Tamaulipas (northeast, Fig. 3b). In contrast, barley straw was distributed in the central region, but there were no municipalities with significant accumulations of the residues (Fig. 3c). Additionally, wheat straw was found in the northern and central parts of the country and the higher potentials were found in Baja California and Sonora (northwest, Fig. 3d).

For Mexico, the main leguminous crops were the beans, a traditional and strategic product of which 50 species are cultivated (30% of the world total), and 20 were included in this study. Beans occupy the second largest amount of seeded land, only after corn (Fig. 4a). However, the crop yields were considered low mainly because almost 90% were raised on rain fed land that was susceptible to weather changes. Therefore, the generated residues barely represented 3% of the PCR without relevant municipalities with a high biomass potential.

The SCR that were represented in the thematic maps were cotton, maguey, coffee and sugarcane with each crop having particular characteristics (Figs. 4b–d and 5a, respectively). The cotton crop was limited only to some northern states with a large residue accumulation (straw and gin trash) in Baja California, Chihuahua and Durango (Fig. 4b). The utilization of these residues to obtain energy could be very convenient because they were not commonly used for animal feed and their physical characteristics, such as the moisture content and density, were adequate for thermo-chemical conversion [26].

Another SCR obtained from typical Mexican products included maguey bagasse. Alcoholic beverages such as pulque, mezcal and tequila are obtained from different varieties of maguey or agave, a succulent plant commercially produced in the central region of the country. Pulque is obtained from *Agave americana* when the sap, a colorless to light yellow liquid called aguamiel (water honey), is fermented. While, mezcal is the generic term for all spirits distilled from the agave, but only spirits derived from *Agave tequilana Weber* (Agave azul) are termed tequila. In this way, the pulque industry produced nearly 1.68 million tons of dry bagasse localized mainly in the Hidalgo state (Fig. 4c). The current uses for maguey bagasse could include boiler fuel, forage, building material and stuffing in furniture. However, uses like forage and building material are not totally convenient due to the low digestibility for animal nutrition and low homogeneity with clay [27]. Thus, the conversion of maguey bagasse to some type of bioenergy is very attractive. The pulque maguey bagasse was an interesting case since it was estimated to be a very large by-product for a small municipality (see Fig. 4c). Certainly, this will be an advantage during the residue recollection and processing into bioenergy because it reduces the collection costs. Thus, despite not being one of the major residues for Mexico, the high concentration of the maguey bagasse (ton/area) makes it very attractive for conversion. In a similar way, the Jalisco state reported a large area of land seeded with agave for obtaining mezcal and tequila. The harvested product, however, was negligible during the studied period and consequently the estimated residues were not significant. Nevertheless, the tequila maguey bagasse in the Jalisco state is still potentially relevant.

Another important SCR for Mexico was coffee, this industry generated 0.51 million tons of solid wastes (pulp and husk), where the main states producers were Veracruz, Oaxaca, and Chiapas (Fig. 4d). These wet by-products constitute a source of severe contamination because of their organic content. The fresh coffee wastes are not recommended for the use as animal foodstuff due to the presence of caffeine; only by processing the pulp is it possible to generate a suitable foodstuff for cattle feedlots. Other solutions have been proposed to mitigate the pollution problems, such as the production of beverages, vinegar, biogas, caffeine, pectin, pectic enzymes, protein and compost [28]. Currently, agave bagasse and coffee solid wastes do not have a widespread use and their availability for bioenergy production is high.

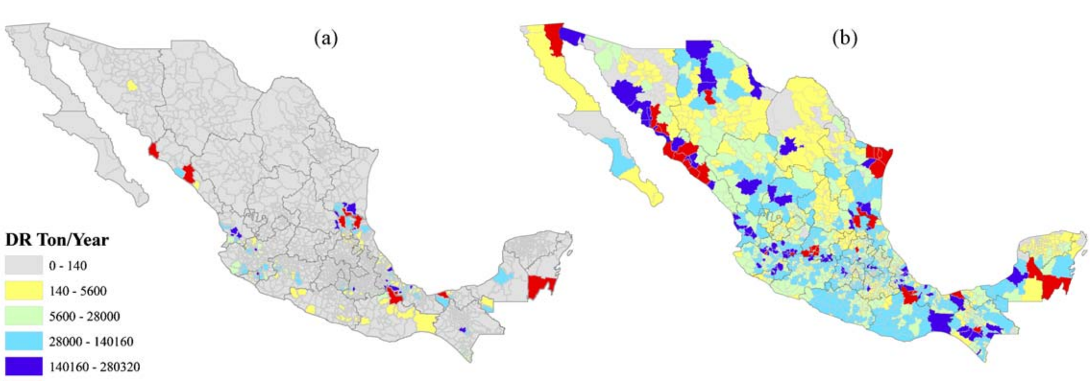

Fig. 5. The distributions of biomass from (a) sugarcane tops/leaves and bagasse and (b) all agricultural activities (total). Notes: the colors indicate the dry residues tons per year. .(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 4
Reported and estimated sugarcane bagasse for Mexico.

State	Reported (05/06)	Humidity %	Reported (05/06) (Dry basis)	Estimated from CRI[a]	No. sugar mills
Campeche	82,555	52.18	39,478	40,124	1
Chiapas	642,178	50.34	318,906	328,641	2
Colima	218,754	49.41	110,668	111,434	1
Guerrero	nr	nr	nr	1,549	0
Hidalgo	nr	nr	nr	10,184	0
Jalisco	1,440,305	50.73	709,638	823,331	6
Michoacán	370,134	50.18	184,401	203,776	3
Morelos	406,549	54.74	184,004	302,102	2
Nayarit	538,707	51.21	262,835	301,657	2
Oaxaca	694,976	50.44	344,430	522,143	3
Puebla	426,965	51.42	207,420	232,908	2
Quintana Roo	462,419	51.22	225,568	246,665	1
San Luis Potosi	1,246,487	51.27	607,413	524,820	4
Sinaloa	534,450	50.94	262,201	343,317	3
Sonora	nr	nr	nr	252	0
Tabasco	521,559	51.56	252,643	257,628	3
Tamaulipas	595,648	50.78	293,178	477,458	2
Veracruz	5,561,242	50.99	2,725,565	2,854,933	22

Notes: [a]crop residue index; adapted from [25].

The last SCR represented in a thematic map was the sugarcane bagasse, which accounted for 7.58 million tons of dry matter (tops/leaves and bagasse) with several municipalities with the highest estimated biomass potential (Fig. 5a). This estimation agreed reasonably well with the data from the National Union of Sugarcane Growers (CNPR) that reported 6.73 million tons, validating somewhat the estimation method we used (Table 4). The sugarcane bagasse was the most potentially useful SCR in North America [23]; where the bagasse was concentrated at 57 sugar mills and currently is the largest commercially used biomass source (after wood) in Mexico. The sugar mills utilized bagasse to generate heat and power for self-consumption. In 2006, 96,956 PJ were generated, representing 2.2% of the total production of primary energy in Mexico [29]. However, the current facilities have obsolete and inefficient equipment and the sugar mills need to increase their energy efficiency through cogeneration schemes to improve their competitive position in the coming years.

Finally, the sum of PCR and SCR (all by-products from Tables 1 and 2) was represented in a thematic map representing the total annual production from 20 crops for Mexico. From Fig. 5b, it can be seen that when all analyzed agricultural by-products were added, new municipalities with a high biomass potential appeared in all Mexican states. Some small municipalities situated from Nayarit to southern Veracruz were of special interest due to their high biomass density which was about 600 tons/km^2 (see Fig. 5b). The key municipalities were those in categories A and B, where the bioenergy production could be sustained from a wide variety of residual materials ensuring long-term supply (Table 5). These data were used to explore the technical bioenergy production from direct combustion and anaerobic fermentation.

3.3. Bioenergy production

The thematic maps were constructed based on six categories that correspond to the annual biomass required (considering a 50% availability) for the energy generation at different capacities. According to [3], the available technologies for electricity generation from the burning of biomass range between 5 and 200 kW, 200 and 1000 kW and >1000 kW. Based on these numbers, the municipalities with an estimated biomass potential between 140 and 5,600 ton/year could supply the requirements of a small electricity generation plant with an installed capacity of 5–200 kW. The main existing technologies in this capacity range include the combustion/steam cycle, the gasification/internal combustion engine and the combustion/stirling engine. However, some of these technologies are still expensive or still in development. Municipalities with an estimated biomass potential between 5,600 and 28,000 ton/year could supply a generation plant of 200–999 kW; the available technologies include the combustion/steam cycle and the gasification/internal combustion engine. Finally, municipalities with the highest estimated biomass potentials (within ranges A–C) are useful for a plant with an installation ranging from 1 to 78 MW; this capacity is comparable with those of diesel or geothermal power plants. Alternatively,

Table 5
Mexican municipalities with the highest estimated bioenergy potential (280,320–2,181,021 tons of dry matter per year).

State	Municipalities	Main crops
Baja California	Mexicali	Wheat, cotton, sorghum
Campeche	Hopelchen	Corn, sorghum
Chiapas	Venustiano Carranza	Sugar cane, corn, beans
Chihuahua	Cuauhtémoc	Corn, wheat, beans
Guanajuato	Abasolo, Irapuato, Pénjamo, Salamanca, Valle de Santiago	Corn, wheat, sorghum, barley, beans
Hidalgo	Cardonal	Maguey, corn, beans
Jalisco	La Barca, San Martin Hidalgo	Corn, wheat, sorghum, barley, sugar cane
Oaxaca	Acatlán de Pérez Figueroa, San Juan Bautista Tuxtepec	Sugar cane, corn
Quintana Roo	Othon P Blanco	Sugar cane, corn, beans, sorghum
San Luis Potosí	Cuidad Valles	Sugar cane, corn
Sinaloa	Ahome, Angostura, Culiacán, Guasave, Navolato, Sinaloa,	Corn, sugar cane, sorghum, beans, cotton, wheat
Sonora	Cajeme, Etchojoa, Navojoa	Wheat, corn, cotton, sorghum, beans
Tabasco	Cárdenas	Sugar cane, corn, sorghum, beans
Tamaulipas	El Mante, Matamoros, Reynosa, Río Bravo, San Fernando, Valle Hermoso	Sugar cane, sorghum, corn
Veracruz	Cosamaloapan de Carpio, Pánuco, Tres Valles	Sugar cane, corn, sorghum, beans

biomass could be converted into bioethanol via anaerobic fermentation, especially in those cases where the moisture content of the biomass material is high and the moisture reduction is needed for a thermo-chemical conversion process, which increases the costs. The potential bioethanol production was estimated using an average conversion factor for lignocellulosic materials. Thus, the municipalities that fall within range A could produce each 261,723 m^3 of bioethanol per year via fermentation, the equivalent to the bioethanol production in Poland, which ranked 14th of the main bioethanol producers in the world in 2006. These estimations were performed in broad terms and there are some limitations in the methods. For instance, the availability of biomass could be less than 50%, the average conversion factor we used might not be accurate for some types of carbohydrates, and the microorganisms used and technology applied could be different. Regardless, the bioethanol production from crop residues should be evaluated seriously in some Mexican municipalities to establish the accurate capacity. The key municipalities for bioenergy production according to our estimations were listed in Table 5. The next step is the field evaluation and establishment of new bioenergy schemes according to the social, economic and environmental situation in each locale. Besides electricity and bioethanol, biomass can be employed to obtain other bioenergies such as biodiesel or biohydrogen through the development of new technologies. This study shows the type, quantity and localization of key crop residues in order to provide support to other studies on bioenergy production.

4. Conclusions

It was estimated that 75.73 million tons of dry matter was generated from 20 crops in Mexico. From this biomass, 60.13 million tons correspond to primary crop residues mainly from corn straw, sorghum straw, tops/leaves of sugarcane and wheat straw. The generation of secondary crop residues accounted for 15.60 million tons to which sugarcane bagasse, corncobs, maguey bagasse and coffee pulp were the main contributors. The distribution of this biomass showed that several Mexican municipalities had a very high by-product potentials where each municipality could have an installed capacity of 78 MW (via direct combustion) or 0.3 million m^3 of bioethanol per year (via anaerobic fermentation). The identification of these municipalities where the biomass potential is high is important since it constitutes the first step towards evaluating the current biomass availability and accurately estimating the bioenergy production capacity from crop residues. Then it will be necessary to propose the best technology for their use at the local level.

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